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The Far Future of Exoplanet Direct Characterization

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Abstract

We describe future steps in the direct characterization of habitable exoplanets subsequent to medium and large mission projects currently underway and investigate the benefits of spectroscopic and direct imaging approaches. We show that, after third- and fourth-generation missions have been conducted over the course of the next 100 years, a significant amount of time will lapse before we will have the capability to observe directly the morphology of extrasolar organisms. Key Words: Far future missions—Direct imaging—High-resolution spectroscopy—Habitable exoplanets—Exo-moons—Surface features. *Astrobiology* 10, 121–126.

1. Investigating More Exoplanets or Habitats

THE FUTURE OF EXOPLANETOLOGY is *a priori* bright since we already know that at least 30% of main sequence stars have one or several super-Earth companions (Mayor *et al.*, 2009). It is likely that there will be two generations of space missions for the direct characterization of exoplanets in the next 15–25 years:

- a first generation with a 1.5–2 m class coronagraph suited for giant planets and nearby super Earths (*e.g.*, Schneider *et al.*, 2009)

followed by

- a second generation consisting of an interferometer (Lawson *et al.*, 2008; Cockell *et al.*, 2009), an external

occulter (Glassman *et al.*, 2009), a large 8 m class coronagraph (visible; Shaklan and Levine, 2008), a Fresnel interferometric imager (Koechlin *et al.*, 2009) or a 20 m segmented coronagraph (super James Webb Space Telescope) for the near IR (Lillie *et al.*, 2001).

In parallel, there will likely be coronagraphic cameras on ground-based extremely large telescopes (like the EPICS camera; Kasper *et al.*, 2008). Here, we have attempted to anticipate what should come next and consider a third-generation mission along with future implications.

There are essentially two directions for astronomers to pursue: (1) the investigation of a larger volume of planets and (2) broader, more detailed characterization of exoplanets for which a candidate biomarker* has been found, to

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*The term biomarker is used here to mean detectable atmospheric species or set of species whose presence at significant abundance strongly suggests a biological origin.

include securing biomarkers as well. We address these possibilities from a scientific point of view rather than one of mission design. We have limited our study to planets whose radius is larger than 0.5 that of Earth, though smaller planets were considered as habitats but may not have evolved in the manner of an Earth-type habitable planet (Lammer *et al.*, 2009).

The detection of yet-undiscovered exoplanets that are the same distance from Earth as those detected by the first two generations of missions will not require a newly devised mission design. To detect a larger number of habitable exoplanets, it will be necessary to observe more-distant stars (hereafter “more distant” means farther than 50 pc), or telluric-like moons of known giant planets in the habitable zone of their nearby star (hereafter “nearby” means closer than 20 pc). In both cases, an increase in angular resolution will be required, either to separate distant planets from their parent star or to separate a telluric companion from its parent giant planet. At 50 pc, the baseline required to separate a planet at 1 AU from the star is $B = 12$ m at 600 nm¹ (respectively $B = 200$ m at 10 micron). But, for distant planets, angular resolution is not sufficient. The collecting area must also scale as D^2 where D is the distance of the planetary system. For a single aperture, this condition is automatically fulfilled; for an interferometer, it is an extra constraint.

2. Deeper Characterization of Most-Interesting Planets

2.1. Spectroscopic and polarimetric approach

One can search for weaker lines (like CO₂ around 9.3 and 10.5 micron in the thermal emission spectrum; Fig. 1), for narrower lines, and for the detailed spectral line shape thanks to higher spectral resolution. The latter case is well illustrated by the double peak of the O₂ band at 760 nm and of O₃ at 9.6 micron, and the CO₂ central peak at 15 micron (Fig. 1). The CO₂ central peak is an interesting diagnostic of temperature inversion in the planetary atmosphere: the central structure of the CO₂ band informs that the upper atmosphere is warmer than the mid-altitude regions, which indicates the presence of an absorbing gas in the former region.² Spectroscopy of giant planets with sufficient signal-to-noise ratios (S/N) and spectral resolution will also allow for measurement of their radial velocity. This will incidentally lead to the determination of the mass of their parent star with an unprecedented accuracy and will allow, by measuring the period and amplitude of the radial velocity variation, detection of moons and measurement of their mass and distance from the host planet. Indeed, the amplitude of the planetary radial velocity variation for a moon at a distance a_{Moon} from its planet is $K = 0.75(M_{\text{Moon}}/M_{\text{Io}})(M_{\text{Pl}}/M_{\text{Jup}})^{-1}(a_{\text{Moon}}/a_{\text{Io}})^{-1/2}$ km s⁻¹. The polarimetric approach will improve the knowledge of clouds, surface, rings, and so forth. (Stam, 2008).

¹We assume that planets must be at an angular distance larger than $2 \lambda/B$ to be observable by a coronagraph.

²For a strongly absorbing gas, the intensity of the emission, at a given wavelength, is essentially that of a blackbody at the temperature of the atmosphere at the altitude where the optical depth τ from outside the background is unity. Consequently, the emission at the center of a band comes from regions at higher altitude than that in the band's wings, revealing the temperature of these regions.

2.2. Direct imaging approach

By progressively increasing the angular resolution, the following can be achieved:

- Detect habitable moons of giant planets by separating the moon's image from that of its parent planet. To separate a moon that is 0.003 AU (the Io-Jupiter distance) from its parent giant planet at 10 AU requires a baseline $B = 400$ m at 600 nm (respectively $B = 7$ km at 10 micron).
- Improve the transit spectroscopy of transiting planets (Schneider, 2000). With a baseline $B = 645$ m at 600 nm, a pixel with a size $= 0.1$ solar radii (R_{Sun}) on a star at 50 pc can be isolated (until now there are only six transiting planets closer than 50 pc); therefore, the S/N can be improved by a factor 10. Note that, for this case, no high-contrast imaging is required; this would be an excellent application of the Stellar Imager project (Carpenter *et al.*, 2009).
- Perform astrometric detection of moons. The astrometric measurement of the displacement of the planet's position due to the pull by a moon offers another way to detect companions to planets. The required baseline is $B = 150,000 (D/10 \text{ pc})(a_{\text{Moon}}/a_{\text{Io}})^{-1}(M_{\text{Pl}}/M_{\text{Jup}})(M_{\text{moon}}/M_{\text{Io}})^{-1}$ km at 600 nm.
- Constrain the planetary radius for transiting planets. The accurate astrometric measurement of the star's centroid during the transit of a planet will give a measurement of the planetary radius independent from the photometry of transits. Indeed, the position of the centroid varies during the transit with a linear amplitude $R_{\text{Pl}}^3/R_{\text{Star}}^2$, which corresponds to a few microseconds for a Jupiter-sized planet at 10 pc. (Schneider, 2000).
- If an isolated (“free floating”) planet is accompanied by a low-mass companion (“moon”), the observation of its orbit will be used to infer the mass of the parent planet.
- Direct measurement of the planetary radius: knowledge of the planetary radius is important since this parameter controls the surface gravity and the Jeans escape of molecules. It can be inferred indirectly from the transit depth (for the few transiting planets) and constrained, with the help of atmosphere models, from the planetary flux in reflected light and thermal emission. A direct measurement is obtained with an imager that has an angular resolution of, say, $0.3 R_{\text{Pl}}$. For a $2R_{\text{Earth}}$ planet at 5 pc, the required baseline at 600 nm is $B = 20$ km.

The ultimate step, currently, would be the direct imaging of surface features (oceans, continents). In this configuration, astronomers can search for the direct detection of the ocean's glint (Williams and Gaidos, 2008). This approach is particularly interesting for imaging *forests* and *savannahs* in order to investigate at a moderate spectral resolution the equivalent of the “red edge” of terrestrial vegetation at 725 nm. To have, for example, a 10×10 pixel image of a $2R_{\text{Earth}}$ planet at 5 pc, a baseline $B = 70$ km is required at 600 nm.

These different configurations are summarized in Table 1 for an image at 600 nm. For an image at 10 micron, the required baseline is multiplied by 17. But, for direct imaging, the angular resolution is not sufficient. A sufficiently large collecting area is also necessary, which adds an additional

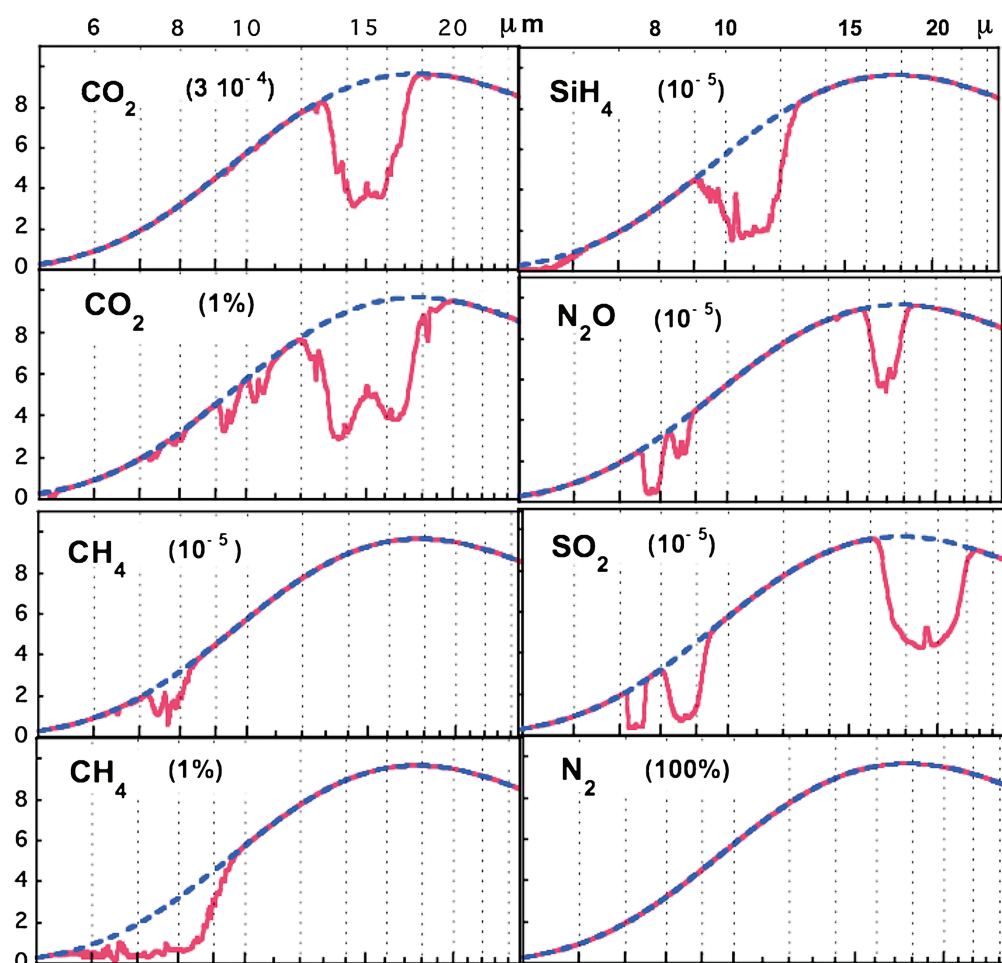


FIG. 1. Spectra of the thermal emission of planets somewhat similar to Earth but with different gases in their atmospheres. The spectral resolution is $\mu\lambda/\Delta\lambda = 200$ and $S/N \sim 100\sigma$. An additional non-IR-active gas, for example, N_2 or O_2 , is assumed with a pressure of 1 bar. The thermal profile of the atmosphere is that of Earth. All the spectral features present are real and show how precise are the fingerprints of gases at this spectral resolution (about 10 times larger than that of Darwin in the present version). In particular, an estimate of the abundance of the gases is possible. The reader is invited to compare the cases of CO_2 and CH_4 at different concentrations (with respect to the 1 bar of inert gas). As explained in the text, the central structure of strong bands, for example, CO_2 , are informative about the thermal structure of the atmosphere (warm stratosphere). Color images available online at www.liebertonline.com/ast.

constraint on sparse aperture interferometers like the “hyper-telescope” (Labeyrie, 1996). To have the same S/N as that for a single pixel image of a planet with a 2 m (respectively 8 m) single aperture, a total area equivalent to a single aperture of 20 m, or 900 one-meter apertures, (respectively 80 m, or 6400

one-meter apertures) is required to have a 10×10 pixel image of a planet.

In conclusion, with a few exceptions, large baselines will be required in the future to perform direct imaging and, in some cases, spectroscopic observations of exoplanets. Therefore, astronomers will inevitably be led to design large interferometers, even at short visible wavelengths. An intermediate step on this pathway would be a mission like the Stellar Imager (Carpenter *et al.*, 2009), for which no additional high-contrast imaging performances are required.

TABLE 1. BASELINE DISTANCES NECESSARY FOR EXO-MOON INVESTIGATIONS TO DIRECT IMAGING OF EXOPLANETARY SURFACE FEATURES (AFTER WILLIAMS AND GAIDOS, 2008)

Objectives	Required baseline at 600 nm
Exo-moon image	400 m
Spectroscopy of a planetary transit image	645 m
Astrometry of a planetary transit image	40 km
Direct measurement of planetary size	20 km
Image of continents/oceans	70 km

3. Other Studies

3.1. Long-term monitoring of most-interesting planets

A better knowledge of behavior and characteristics of the most-interesting planets will be provided by long-term monitoring programs over the course of months to years. These programs will lead to an improved knowledge of these planets’ diurnal rotations, random cloud coverage, and

seasonal and volcanic events. A particular application is the detection of moons by *mutual events* during a continuous photometric monitoring of the planetary flux. These mutual events will reveal the presence of a moon by the shadow they project on the planet, by their disappearance in the planet's shadow, and by the primary and secondary transit with the parent planet (Cabrera and Schneider, 2007).

3.2. "Technosignatures"

Beyond standard biosignatures, another type of signal far from equilibrium can be seen as *technosignatures*, that is, spectral features that cannot be explained by complex organic chemistry, such as laser emissions. In the present state of our knowledge, we cannot eliminate these signals *a priori*, though we have no guiding lines with which to search for them. For instance, in the present Earth atmosphere, chlorofluorocarbon (CFC) gases are the result of technological chemical synthesis. Observed over interstellar distances, they would reveal to the observer the presence of technology on our planet. The detection of their absorption spectrum on an exoplanet would require a spectral resolution of at least 100 around 10 micron (See Fig. 2). Of course, in an exoplanet, CFCs would probably be replaced by other technosignatures. Another approach would be to detect artificially produced light (*e.g.*, laser light). On Earth, the present total energy production is about 40 TW. This represents one thousandth of the sunlight energy reflected by the whole Earth. With regard to an exoplanet, this means that artificial light produced with the same power would be lost in the background noise of the stellar light reflected by the planet. This situation can be circumvented by observing the planet in the nightside only. But then the spatial resolution should be at least $0.3 R_{Pl}$, which corresponds to a baseline B of 70 km for a $2 R_{Earth}$ planet at 5 pc. To be detected with a S/N equivalent to the detection of the reflected stellar light by the whole planet with a 1.5 m telescope, the collecting area required to detect artificial light one million times fainter should be one million times larger, that is, correspond to a single aperture with a diameter $B = 1.5$ km. Another type of technosignature could go beyond the suggestion to detect artificial constructions by

their transits in front of stars (Arnold, 2005); this kind of detection would be improved by resolving the stellar disc.

4. The Very Long-Term Perspective

If around 2020–2030 we have found a promising biomarker candidate on a nearby planet [for instance, around Alpha Centauri (Guedes *et al.*, 2008)], such a discovery would trigger two kinds of projects:

- *Direct visualization of living organisms.* To detect directly the shape of an organism 10 meters in length and width, a spatial resolution of 1 meter would be required. Even on the putative closest exoplanet, Alpha Centauri A/B b, the required baseline would be at 600 nm $B = 600,000$ km (almost the Sun's radius). In reflected light, the required collecting area to obtain 1 photon per year in reflected light is equivalent to a single aperture of $B = 100$ km. In addition, if this organism is moving with a speed of 1 cm s^{-1} , it would have to be detected in less than 1000 s. To get a detection in 20 minutes with a S/N of 5, the collecting area would correspond to an aperture $B = 3$ million km. All these numbers are unrealistic, unless laser-trapped mirrors, as proposed by Labeyrie *et al.* (2005), are realized (in their present conception, laser-trapped mirrors are fragile in the solar wind).
- *Exploration of nearby stars.* The possibility to explore *in situ* nearby stars at a speed of $0.3c$ has often been invoked (see, for instance, Crawford, 1990; Bjørk, 2007). At this speed, however, the problem of shielding against damaging cosmic rays and interstellar dust would threaten the entire mission. According to Semyonov (2009), a water shell of 1 m in thickness would be sufficient protection, but then there is the problem of accelerating an object up to $0.3c$. As for the threat posed by interstellar dust, a 100 micron interstellar grain at $0.3c$ would have the same kinetic energy as a 100 ton body at 100 km h^{-1} . No currently available technology could protect against such a threat without a spacecraft that has a mass of hundreds of tons, which, in turn,

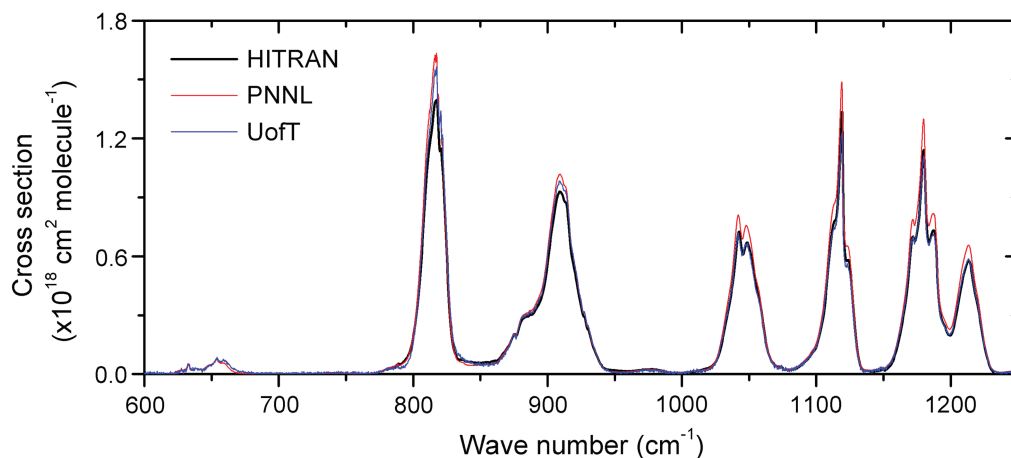


FIG. 2. Spectrum of CFC-113 (Le Bris *et al.*, 2006), showing good agreement between the HITRAN model and Pacific Northwest National Laboratory (PNNL) and University of Toronto (UofT) measurements. Color images available online at www.liebertonline.com/ast.

would be extremely difficult to accelerate up to 0.3 c. A way around all this would be to employ a travel velocity of only a few hundred km s⁻¹, as is the case for the “The Project” (Kilston, 1999). But then the journey to Alpha Centauri would take 10,000 years.

Regardless of the approach, it seems impossible to have direct visual contact with living organisms on a nearby exoplanet over the course of centuries, at least in the framework of foreseeable physical and technological concepts, and what physics will be in 1000 years is not reasonable to anticipate. We are thus limited by a kind of conceptual or knowledge horizon.

5. Conclusion

Within a period of approximately 200 years, it can reasonably be expected that high-resolution spectroscopy and then high-angular direct imaging will improve considerably our knowledge of nearby exoplanets and possible global biomarkers. For the latter approach, large interferometers will be inevitable. The highly desirable next step would be direct visual observation of the morphology of life-forms on these planets, should such life-forms exist. Unfortunately, technological obstacles will lead to a frustrating period of many centuries before this hope can be realized, and we are perhaps as far from this epoch as Epicurus was from seeing the first *other worlds* when, 23 centuries ago, he predicted the existence of these planets (Epicurus, 300 BCE).

Abbreviations

CFCs, chlorofluorocarbons; S/N, signal-to-noise ratio.

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